

Modelling the 1.8 MeV Sky: Tests for Spiral Structure

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Abstract. COMPTEL imaging analysis revealed a patchy, asymmetric distribution of diffuse 1.8 MeV emission along the Galactic plane, which is attributed to the decay of radioactive ^{26}Al in the ISM. If massive stars were the major source of Galactic ^{26}Al , the 1.8 MeV emission should be asymmetric and trace the spiral arms of the Galaxy, presumed site of massive star formation. Using model fits, we indeed find weak evidence in the COMPTEL data that the observed 1.8 MeV emission is at least partly confined to spiral arms. We derive a total Galactic ^{26}Al mass of $2.5 M_{\odot}$ from which at least $0.7 M_{\odot}$ can be attributed to massive stars.

Key words: gamma rays: observation – nucleosynthesis – Galaxy: structure

occurs predominantly inside the spiral arms, especially in the case of massive stars. Thus the 1.8 MeV emission profile should reflect the structure of these arms which is thought to be asymmetric with respect to the Galactic centre. Previous analysis of COMPTEL data indeed revealed an asymmetry with more 1.8 MeV emission from the southern (Galactic longitude $l=180^{\circ}$ - 360°) than from the northern ($l=0^{\circ}$ - 180°) Galaxy (Diehl et al. 1995a). Additionally, the 1.8 MeV sky map shows lumpy emission and ‘hot spots’. Prantzos (1993) noted that some emission maxima coincide with the assumed tangential directions of Galactic spiral arms. Thus a detailed study of the spiral arm hypothesis is of interest. In this paper we will report on a comparison of COMPTEL phase I+II data (May 1991 - August 1993) to models of Galactic ^{26}Al distribution with special emphasis on spiral structure.

1. Introduction

Since the discovery of the 1.8 MeV gamma-ray line emission from radioactive ^{26}Al by Mahoney et al. (1982), the questions of its origin and its distribution along the Galactic plane stimulated a wave of research (see review of Prantzos & Diehl 1995). Core collapse supernovae (SNe), Wolf-Rayet (WR) stars, asymptotic giant-branch (AGB) stars, and O-Ne-Mg novae were suggested as possible sites of significant ^{26}Al creation. Early works assumed that the large mean lifetime of $\tau_{26} \sim 10^6$ yr and the low ^{26}Al yield per source will lead to a smooth and symmetric distribution of 1.8 MeV emission. Prantzos (1991) was the first who dropped the assumption of an axisymmetric source distribution in the Galactic plane if massive stars were the dominant ^{26}Al producers. He argued that star formation

2. Instrument and Data Analysis

COMPTEL has an energy resolution of $\sim 8\%$ (FWHM) at 1.8 MeV and an angular resolution of 3.8° (FWHM) within a wide field of view of about 1 steradian. γ -ray photons are measured by their consecutive interactions in two parallel detector planes where an incident photon is first Compton scattered in the upper layer and then absorbed (although often not completely) in the lower layer. A detailed description of the instrument can be found in Schönfelder et al. (1993). We analyzed the COMPTEL data in the three-dimensional imaging data-space which is spanned by the scatter direction (χ, ψ) and the Compton scatter angle $\bar{\varphi}$ of the incident photons. For the ^{26}Al study, we applied a 200 keV wide energy window, centred on 1.8 MeV, to the data. This encloses 48% of all detected events from a celestial 1.809 MeV source.

The Galactic models are represented as ^{26}Al source density functions. 1.8 MeV model intensity maps are eval-

uated by integration of these functions for a grid of Galactic longitudes l and latitudes b along the corresponding lines of sight (Prantzos & Diehl 1995). The convolution of these maps with the instrumental point-spread-function leads to model distributions of 1.8 MeV source events in the data-space. By maximization of the overall data-space likelihood, the source models are fitted along with a model for the instrumental background to the data. The background model was derived using independent measurements at adjacent energy bands. Data-space analysis in this approach suppresses continuum emission and reveals only the sources of pure 1.8 MeV line emission (Knödlseeder et al. 1996). To reduce systematic uncertainties, the unknown $\bar{\varphi}$ -profile of the background model was adjusted by the fit.

We tried to eliminate impacts of possible local 1.8 MeV foreground emission from our Galaxy-wide study: for the observed 1.8 MeV emission in Vela, probably associated with the Vela SNR (Oberlack et al. 1994, Diehl et al. 1995b), and in Cygnus, probably related to some nearby star forming regions (del Rio et al. 1994), two source components with free intensity were included in the background model. Both were chosen to have uniform intensity within a circle of 10° in radius, centred on $(l, b)=(259^\circ, 0^\circ)$ for Vela and on $(l, b)=(83^\circ, 0^\circ)$ for Cygnus. Also, the region of the outer Galaxy between $l=120^\circ$ and $l=240^\circ$ was excluded from the analysis, because the 1.8 MeV sky-map shows significant emission near the anticentre which is probably due to nearby ^{26}Al sources implied by its wide latitude extension.

The maximum likelihood technique (de Boer et al. 1992) was applied to determine the parameters and the significance of the source models. It uses the parameter $-2\ln\lambda$ to quantify the model-data agreement, where λ is the maximum likelihood ratio $L(\text{background})/L(\text{source} + \text{background})$. Higher $-2\ln\lambda$ values signal a better fit of the model to the data. Formally, $-2\ln\lambda$ obeys a χ_n^2 probability distribution, where n is the number of free parameters of the source model. Roughly, the significance of the source model over background follows $\sqrt{-2\ln\lambda}$, which is exact for $n = 1$. We visualized the model-data agreement for each fit by a longitude scan of the data-space for measurement and fitted model using the software collimation technique (Diehl et al. 1993). An acceptance circle of 3° was selected which implies an effective angular resolution of 10° - 12° for the scans.

3. Axisymmetric models

3.1. Tracers of Galactic ^{26}Al

We start our discussion with axisymmetric models for which the source density function only depends on the galactocentric radius R and the distance z from the Galactic plane. For the vertical profile we assumed throughout a uniform exponential law with scale height z_0 . Un-

fortunately, the Galactic distribution of all ^{26}Al candidate sources is poorly known because of the combined effects of visual obscuration, uncertain sample completeness, and small-number statistics. Consequently, we model their spatial distribution by tracers observed either in our Galaxy or in external spiral galaxies. Many such tracers have been proposed up to now, and we discuss only a few that seem to be the most appropriate (see also Diehl et al., this volume). For this purpose we divide the candidate sources in two classes:

Young population: Stars younger than $\sim 10^8$ yr are classified as extreme Population I objects. From the ^{26}Al candidate sources, massive AGB stars, SNe, and WR stars fall in this group. The Galactic distribution of these objects has a small scale height ($z_0 \sim 90$ pc) and can be traced either by giant H II regions or giant molecular clouds (GMCs). The distribution of GMCs is generally inferred from radio observations of the CO $J = 1 \rightarrow 0$ rotational transition at a wavelength of 2.6 mm. Under the simplifying assumption that the ^{26}Al emissivity is proportional to the molecular gas mass surface density we used the radial H_2 distribution given in Fig. 1 of Dame (1993). We added a Galactic centre flat disk component with radius of 500 pc to account for the nuclear disk which is present in all CO surveys. The total mass of this component was left as free parameter, because the star-formation efficiency and therefore the ^{26}Al yield in the Galactic centre might differ from that in the Galactic disk.

Intermediate population: Low-mass AGB stars ($M < 2M_\odot$) and novae have ages greater than a few 10^9 yr. It is believed that these objects follow the luminosity profile of the Galaxy which is composed of a disk and a bulge component (Bahcall & Soneira 1980). The disk is assumed to be of the exponential form $\sigma(R) \propto \exp(-R/R_0)$, where $\sigma(R)$ is the galactocentric surface density and R_0 is the radial scale length of the disk. Estimates for R_0 have been derived by numerous workers and span the enormous range of 1 to 6 kpc (Wainscoat et al. 1992, Kent et al. 1991). Patterson (1984) found a disk scale height of ~ 180 pc for the intermediate population. The bulge is commonly described as an oblate spheroid with an exponential density decrease. Wainscoat et al. (1992) fitted *IRAS* data using $\rho(R, z) \propto x^{-1.8}e^{-x^3}$, where $x = \sqrt{R^2 + k_e^2 z^2}/R_e$, $k_e = 1.6$ and $R_e = 2.0$ kpc are the axis-ratio and effective radius, respectively. However, the relevance of the bulge component for ^{26}Al sources is questionable because it possibly contains only objects older than 10^{10} yr, hence no ^{26}Al producing AGB stars or O-Ne-Mg novae.

3.2. Results and discussion

From the fit of an exponential disk we found an optimum scale length of 5_{-2}^{+5} kpc and scale height of 180_{-130}^{+240} pc for the Galactic 1.8 MeV emission (all quoted uncertainties are statistical 2σ errors). The scale length

is on the upper side of estimates at other wavelengths. The scale height is only weakly constrained because of the poor angular resolution of COMPTEL, but it overlaps with estimates which reach from 90 pc to 325 pc for the youngest and oldest stellar populations, respectively (Bahcall & Soneira 1980). For comparison of the data with the intermediate stellar population, we fixed the scale height to 180 pc and added the bulge as additional component. The inclusion of the bulge gave only marginal, insignificant, fit improvement: there is no evidence for a bulge on top of an exponential disk in our 1.8 MeV COMPTEL data (Table 1). To test for the young stellar population we fitted CO models with and without a nuclear disk in the Galactic centre (GC) to the data. For both cases the optimum scale height was 110^{+100}_{-70} pc which is consistent with the scale height of the molecular gas. We find preference for the model with the nuclear disk component at the 3σ significance level, but the likelihood ratios for both CO models are slightly worse than that of the ‘best disk’.

As an illustration for axisymmetric models the longitude scan of the ‘best disk’ fit, derived by software collimation, is shown in Fig. 1 (note, that this scan technique has only poor angular resolution (10° – 12°), hence sharp features in the data are smeared out, large-scale trends are emphasized at the cost of not showing small-scale fit inadequacies). Obviously, the ‘best disk’ already gives a reasonable first-order description of the 1.8 MeV data. However, there are some significant discrepancies between the model and the data. While there is a lack of counts in the northern Galaxy between $l \approx 50^\circ - 75^\circ$, excess counts are found around $l \approx -50^\circ$ and $l \approx -75^\circ$ in the southern Galaxy. It is obvious that this north-south asymmetry cannot be explained by any axisymmetric model. Actually, the ‘best disk’ is the optimal balance of this asymmetry which explains why it yields the best likelihood ratio of all axisymmetric models. Therefore, we conclude that objects with a smooth, symmetric distribution (as expected for low-mass AGB stars or novae) cannot be the sole source of ^{26}Al in the Galaxy.

4. Spiral models

We now drop the assumption of an axisymmetric source distribution and investigate the hypothesis that the Galactic 1.8 MeV emission is correlated with spiral arms. Unfortunately, the spiral structure of the Galaxy is not well established and even the number of spiral arms is under debate (e.g. Elmegreen 1985). The most reliable large-scale picture of the Galactic spiral structure is probably deduced from the distribution of giant H II regions. Their distances can be estimated spectro-photometrically from the distances to the exciting O/B-stars and do not depend on models of Galactic rotation (in contrast to spiral structure derived from H I or CO surveys). We adopt the spiral model of Taylor & Cordes (1993) who adjusted a four-arm

Table 1. Fit results for axisymmetric models. The last two columns contain the total Galactic ^{26}Al mass in the disk and in a possible Galactic centre (GC) component. We quote 2σ statistical errors for the mass which generally increase with the number of free model parameters.

Model	R_0 (kpc)	z_0 (pc)	$-2 \ln \lambda$	Disk ^{26}Al mass (M_\odot)	Centre ^{26}Al mass (M_\odot)
Best disk	5*	180*	418.0	3.2 ± 1.1	-
+bulge	6*	180	418.1	3.3 ± 0.5	0.07 ± 0.19
CO	-	110*	403.8	2.4 ± 0.5	-
CO+GC	-	110*	412.3	2.2 ± 0.5	0.17 ± 0.12

* parameters optimized by the fit

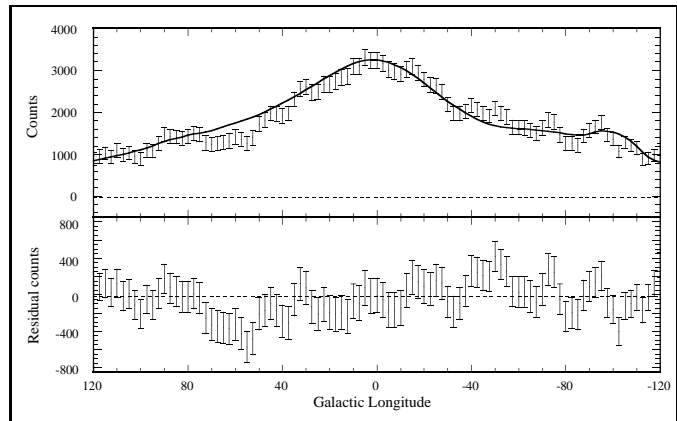


Fig. 1. Longitude scan derived by software collimation for the ‘best disk’ fit. The upper panel shows the background subtracted profile, in the lower panel the residual counts are plotted (observed-predicted). Note, that we directly compare measured to predicted counts, thus an axisymmetric distribution must not lead to a symmetric longitude profile because of exposure variations along the Galactic plane.

spiral pattern based on giant H II regions and radio-survey tangent points to pulsar dispersion measures and interstellar scattering measurements. Their aim was to obtain a quantitative model for the distribution of free electrons in the Galaxy to estimate pulsar distances from dispersion measures. Recently, Chen et al. (1995) pointed out that free electrons could be a valuable tracer of ^{26}Al because they are mainly produced by the massive star population. Therefore we directly compare the Taylor & Cordes (TC) free-electron model to the COMPTEL 1.8 MeV data. We tentatively added a nuclear disk component (c.f. section 3.1) of 90 pc scale height in the Galactic centre region where the TC model is only weakly constrained by the pulsar data.

The likelihood ratio for both the TC model with and without the nuclear disk component is better than that of the best exponential disk (see Table 2). From the longitude

scan (Fig. 2) we see that the TC model fits the north-south asymmetry better than the axisymmetric models. Besides the global asymmetry, the TC model also explains the two excesses at $l \approx -50^\circ$ and $l \approx -75^\circ$ due to the presence of spiral arm tangent points in these directions. Additional, but less outstanding tangent points of the model at $l \approx -30^\circ$, $l \approx 30^\circ$, and $l \approx 50^\circ$ are almost invisible in the scan because they are smeared out due to the poor angular resolution of the software collimation technique (see above). However, except the $l \approx -30^\circ$ tangent, all spiral arm tangent points of the model coincide well with count excesses in the data supporting the hypothesis that Galactic ^{26}Al is at least partly confined to spiral arms.

We also studied a more analytical model which consists of the TC spiral pattern on top of an exponential disk. This model allows that some massive stars lie outside the spiral arms, but would also be valid if Galactic ^{26}Al has a composite low- and high-mass star origin. From the fit we obtained an optimum disk scale length of $3.5^{+2.5}_{-1.5}$ kpc and scale height of 180^{+240}_{-130} pc. The likelihood ratio is similar to that of the TC+nuclear disk model, thus the data cannot tell us which of the two models is a more reliable representation of the Galactic ^{26}Al distribution. The total ^{26}Al mass of $2.7 M_\odot$ is comprised of $2.0 \pm 0.7 M_\odot$ for the disk and $0.7 \pm 0.3 M_\odot$ for the spiral arms. Therefore, the total Galactic ^{26}Al mass created by massive stars is bracketed by $\sim 0.7 M_\odot$ from the arm component of the disk+arm model and by $\sim 2.5 M_\odot$ from the TC free electron model.

Table 2. Fit results for spiral models.

Model	$-\ln \lambda$	Total Galactic ^{26}Al mass (M_\odot)	Nuclear disk
TC	419.6	2.6 ± 0.3	-
TC+nuclear disk	423.2	2.5 ± 0.4	0.11 ± 0.06
Best disk+arms	423.7	2.7 ± 0.8	-

5. Conclusions

We have compared the COMPTEL 1.8 MeV data from observation phases I+II to axisymmetric and spiral-arm models of Galactic ^{26}Al distribution. All models were detected at a significance level of $> 20\sigma$ above background. To first order, the observed 1.8 MeV emission is well represented by axisymmetric models. However, details of the data like the north-south asymmetry and some regions with significant count excesses are better described by models which incorporate the Galactic spiral structure. Our best fit model holds a total Galactic ^{26}Al mass of $\sim 2.5 M_\odot$ from which at least $0.7 M_\odot$ are produced by massive stars. Thus, massive stars clearly contribute to the observed ^{26}Al in the Galaxy but we can certainly not

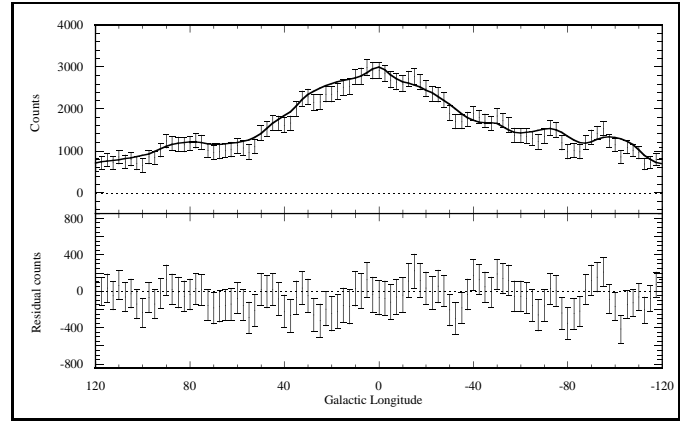


Fig. 2. Longitude scan derived by software collimation for the Taylor & Cordes spiral model including a nuclear disk component.

exclude from this work that a large fraction of ^{26}Al is produced by low-mass AGB stars or novae.

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